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# COOPERATIVE INVESTIGATION OF JET FLOWS

ANNUAL TECHNICAL REPORT
1981 - 1982

BY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

With the help of a carefully designed and operated laser doppler velocimeter, data were collected in an axisymmetric jet under controlled laboratory conditions. This data were found to conserve momentum; a problem which plagued most previous measurements. This resulted in near perfect agreement with the predictions of Reynolds stress models of turbulent jets. Far and near field sound measurements for a range of Mach and Reynolds numbers provided clues to the mechanism which lead to enhancing the broad band noise at high Reynolds numbers in presence of pure-tone excitation while suppressing it at low Reynolds numbers. At low

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Reynolds numbers the excitation leads to augmentation of the coherent large scale structures. At sufficiently high Reynolds number, noise due to the interaction of the wave-like structures with incoherent fine-scale turbulence may be dominant. This may also explain the difference in level of radiated noise from high and low Reynolds number jets. Controlling the jet with pure tone excitation, that enhances the helical mode of its instability, resulted in a suppression of the radiated noise by approximately 8dB. In general we find that a great deal of appreciation of the jet flowfield can be gained by viewing the jet as a nonparallel shear flow which is always susceptible to instabilities. In all cases, the instability of turbulent layers and the role of helical modes and upstream influence appear to be key mechanisms in our findings.

# Cooperative Investigation of Jet Flows

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With the help of a carefully designed and operated laser doppler velocimeter, data were collected in an axisymmetric jet under controlled laboratory conditions. This data were found to conserve momentum; a problem which plagued most previous measurements. This resulted in near perfect agreement with the predictions of Reynolds stress models of turbulent jets. Far and near field sound measurements for a range of Mach and Reynolds numbers provided clues to the mechanism which lead to enhancing the broad band noise at high Reynolds numbers in presence of pure-tone excitation while suppressing it at low Reynolds numbers. At low Reynolds numbers the excitation leads to augmentation of the coherent large scale structures. At sufficiently high Reynolds number, noise due to the interaction of the wave-like structure with incoherent fine-scale turbulence may be dominant. This may also explain the difference in level of radiated noise from high and low Reynolds number jets. Controlling the jet with pure tone excitation, that enhances the helical mode of its instability, resulted in a suppression of the radiated noise by approximately 8dB. In general we find that a great deal of appreciation of the jet flowfield can be gained by viewing the jet as a nonparallel shear flow which is always susceptible to instabilities. In all cases, the instability of turbulent layers and the role or helical modes and upstream influence appear to be key mechanisms in our findings.

## I. BACKGROUND

The broad objectives of this three university effort have been:

1) To determine the relevance, inception and three dimensionality of large scale structures in the mixing region of an axisymmetric jet.

2) To determine whether or not these large scale structures play an important role in the radiated noise.

3) To quantify the above conclusions so that the results can be used for evaluation of jet noise theories and for prediction of radiated noise.

4) To develop means ot controlling managing or suppressing those large scale structures for the goal of reducing the radiated noise

This investigation is being carried out in three parts. At the Illinois Institute of Technology, a detailed study is underway to determine the importance of Reynolds number and initial conditions on the dynamics of the near field of the jet, which influerces the downstream evolution of large scale structures. At the University of Minnesota, a detailed study of the radiated noise field in a similar facility is being carried out. At SUNY/Buffalo, a detailed study of the turbulent velocity field is being carried out utilizing Lumley's orthogonal decomposition technique to obtain a deterministic and objective picture of the three dimensional large scale structures. These experiments, with each university utilizing similar facilities, will yield quantitative data to determine whether and how large scale structures in jets contribute to the observed radiated noise.

The specific objectives of each university for the previous year along with the status of the current research is presented in the following section.

## II-A ILLINOIS INSTITUTE OF TECHNOLOGY

### Objectives

During the last year we focused on several objectives:

1) Examine the initial instability characteristics of a natural "axisymmetric" free jet and determine if other than axisymmetric instabilities and large-scale structures play an important role in the development of the jet. If so, determine how they affect the simple axisymmetric thinking about jet development. In addition, assess the importance of the non-parallel flow or divergence of the jet in regard to its instabilities.

2) Investigate the effect of initial conditions and Reynolds number on the nature of the developing instabilities. The initial conditions can be altered by changing the state of the exit boundary layer; increasing the Reynolds number with a constant core intensity or by fixing the Reynolds number and altering the disturbance level at the exit by utilizing suitable upstream grids. A close relation between initial conditions and jet evolution can then be derived.

3) Examine the evolution of the subharmonic mode. Utilizing near-field pressure measurements and velocity measurements in the jet, conduct experiments to prove or disprove the feedback mechanism as well as establish the degree of importance of pairing in natural jets. Also, examine the upstream influence of downstream evolving modes, constantly keeping initial conditions in mind.

4) Determine if a natural coupling exists between the initial instability of the jet ($\alpha f_i^{3/2}$) and the "final" Strouhal mode ($\alpha f_i$); and if so, is it affected by the initial conditions? In addition, determine whether the coupling is natural and simply enhanced by forcing or whether forcing imposes this condition on the flow.

Near the end of the potential core, the jet maintains its maximum characteristic velocity with the most mass flux because of entrainment. The large scales at the end of the near region of the jet may very well be the most energetic of the noise generating eddies. The characteristic frequency of these eddies appears to be the dominant frequency in the far-field jet noise. If we are to understand the relation between the jet flow and its noise field in depth, we need the above information well documented and understood.

## Results

Utilizing simultaneous near-field pressure and velocity measurements along with multiple flow visualization techniques, experiments have been conducted with the above objectives in mind. The results of these experiments are summarized in this section.

When the exit boundary layer is laminar, the natural jet is initially alternately unstable to axisymmetric and helical modes. The axisymmetric mode scales at a constant Strouhal number of 0.013 based on momentum thickness, while the helical mode scales at a constant Strouhal number which is 20% higher than this value. This behavior is independent of Reynolds number ($10^4$-$10^5$) and initial conditions when properly scaled. The relative occurrence of these modes is highly dependent on the initial disturbance characteristics at the jet exit. It is only at low Reynolds number and for low initial disturbance levels that the axisymmetric mode dominates initially. As either of these variables increase, both modes become equally important.

This importance arises when examining the spreading rate of the jet. At low core disturbance levels of approximately 0.05%, the axisymmetric mode is dominant and the spreading rate of the jet is largest. As the probability of observing an axisymmetric or helical mode approaches 0.5, the spreading rate is 10% less than for the axisymmetric dominated flow. This behavior could account for the large scatter in spreading rates in the literature. It is not possible to determine its universality however, because of the undocumented initial conditions in previous experiments.

When the initial axisymmetric mode grows in amplitude to about 1% of the jet velocity, a secondary resonant interaction develops and leads to the pairing of axisymmetric vortical structures. The downstream position of this resonant interaction occurs after two wavelengths of the initial axisymmetric mode. At this position the subharmonic wave has obtained the same phase speed as the fundamental and the two waves are out of phase. This point is also associated with the initial roll up of the jet and the first downstream position where strong entrainment into the jet is observed.

Due to the alternating nature of the initial instability of the jet, the axisymmetric and helical modes interact nonlinearly to develop numerous sum and difference modes. As these modes develop downstream, the subharmonic mode also interacts nonlinearly with these modes. Just downstream of the peak amplitude of these latter nonlinear interactions, strong three-dimensionality and transition to turbulent flow are observed.

Due to the multiplicity of spectral peaks recorded both in the mean shear region and in the potential core, the true identification of these modes cannot be determined without azimuthal information. Lack of proper identification of these modes, coupled with low level coherent incidental disturbances in a number of facilities, has led to the previously reported nonideal behavior of steps in the initial instability frequency as a function of Reynolds numbers. These steps are not related to a feedback mechanism or pairing.

Each ot these instability modes has a pressure field associated with it which is coherent with the velocity fluctuations on the jet over the entire growth and decay range of that mode. This pressure field acts linearly at the nozzle lip and sets both the initial disturbance level and azimuthal distribution for each mode. The initial amplitudes are highest for the nonlinear difference modes and the subharmonic mode. In fact, the initial amplitudes of these modes are an order of magnitude larger than that of the initial axisymmetric mode. Previous experiments have had too high a background disturbance level to be able to observe this.

Under extremely low disturbance levels, a natural coupling is observed between the initial instability of the jet and the Strouhal mode associated with the final stages of the potential core. This was observed when the two frequencies were related by integral multiples of two. This coupling is not related to the pairing process as previously believed. At this coupling position, subharmonic pressure radiation is increased leading to a reinforcement of the axisymmetry of the flow.

When the exit boundary layer is turbulent, a linear instability based on the mean profile is observed near the nozzle where the frequency scales at a constant Strouhal number of 0.024 based on the local momentum thickness. The development of the jet from the nozzle lip to the end of the potential core is found to be adequately described by locally applying linear spatial theories to account for the slow divergence of the jet. The instability-generated large scales have been observed to develop initially in both axisymmetric and helical modes.

In summary, for these turbulent jets with laminar or turbulent initial conditions, a great deal of appreciation of the flowfield can be gained by viewing the jet as a nonparallel shear flow which is always susceptible to instabilities. Viewing the jet as a shear layer first and then as a jet near the end of the potential core, may have led to many misleading perceptions. In any case, the instability of turbulent layers and the role of helical modes and upstream influence appear to be key mechanisms in our findings.

Now that the development of the near region of the jet is understood, we have focused our attention on obtaining quantitative information on the instantaneous three dimensional nature of the large scales between 3 and 10 diameters downstream of the jet exit. Two-dimensional reconstruction techniques have been modified to account for the three-dimensionality of the flowfield in order to extract the low wavenumber structures. Information from this experiment will clearly set the proper importance of coherent large scale structures in this region of the jet.

## II-B University of Minnesota

### Overview

The year was spent meeting several objectives:

1. Determine in a definitive manner the features of the acoustic field surrounding low Reynolds number jets and determine if there are any significant differences from the sound radiated from high Reynolds number jets.

2. Develop the experimental techniques necessary to identify sound source distribution in jet flows and relate these observations to observations of coherent structure using flow visualization.

3. Develop a theoretical framework for the observations.

The first objective has been completed and the results have been published (5). A summary is presented below. Several experimental methods were developed during the reporting period. An acoustic excitation technique allows selectively forcing the jet into several different modes of acoustic radiation. In one case the jet flow can be modified such that significant reductions in jet noise are experienced. A flow visualization technique using a smoke wire phase - locked to the acoustic excitation permits observation of coherent structure. A polar correlation technique, using two microphones in the far field has been developed for the measurement of sound source distribution in the flow.

Theoretical modelling of the near field pressure has enabled us to more clearly understand the spectral characteristics of the near field pressure signal.

### Results

#### Acoustics of Low Reynolds Number Jets

An extensive survey of the spectral characteristics of the far-field noise has revealed no effect of Reynolds number in the range $16 \times 10^3 < Re < 250 \times 10^3$. However, the noise level is found to be about 7dB lower than high Reynolds number experiments ($Re > 3 \times 10^5$) to be carried out at other facilities (Fig. 1). Discussions concerning this apparent discrepancy have led to the conclusion that although Reynolds number appears to be the decisive parameter, other factors must be considered, particularly the initial conditions at the jet exit.

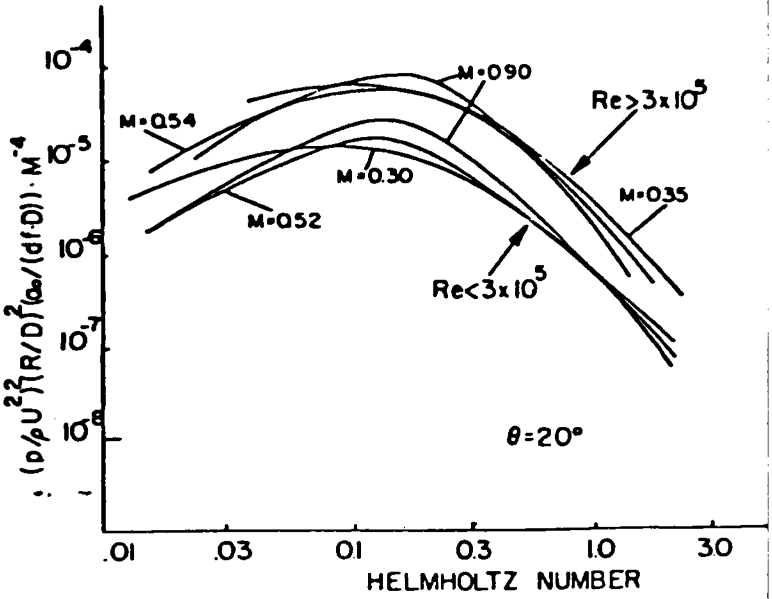
Correlation of frequency dependent data is made <u>without</u> the Doppler correction $(1 + U_c \cos\ )$. Preliminary analysis of the data appears to indicate that this correction would be inappropriate, implying that the sound sources act as though they were stationary. Furthermore, the data appear to correlate better with Helmholtz number $(\frac{fd}{a_o} = \frac{d}{\lambda})$ than with Strouhal number $(\frac{fd}{U_J})$. One possible explanation is that the noise from small scale turbulence is modulated by a large, wave-like structure producing a sound field with a characteristic wave length that is proportional to the wave length of the structure which in turn scales with jet diameter.

Normalized near field pressure spectra <u>decrease</u> in amplitude with <u>increasing</u> Mach number as opposed to far field noise which increases with Mach number (Fig. 2). Pressure measurements by Armstrong et al within the jet mixing layer do not show a similar attenuation with Mach number. This may indicate that there is not a significant effect of Mach number on the noise producing fine-grained turbulence, but that there is a compressibility effect on the non-propagating, irrotational pressure field surrounding the jet. This point is underscored by observing the development of pressure spectra as one moves from the near field to the far field as shown in Fig. 3. It is found that at a distance of two wave lengths $(k \cdot y \sim 2.0)$ the pressure fluctuations exhibit a spatial decay of 6dB per doubling of distance, characteristic of acoustic disturbances. This is consistant with a simplistic acoustic model consisting of a single quadr pole located in the center of the mixing region. It is easily shown that the active (propogating) part of the pressure field dominates the reactive part at distances in excess of 1.75 wave lengths.

The observed increase of normalized noise intensity with Mach number is also predicted by an acoustic model with the assumption that source amplitude is independent of Mach number. Further, comparison between near and far field pressure spectra indicate that a substantial portion of the energy in the near field pressure spectra is non-propagating. All this implies that the large scale (essentially irrotational) structure may exhibit strong compressibility effects which can explain the dependence of jet development on Mach number effects. This further fits with the concept of a large scale, wave-like structure modulating the noise produced by a collection of essentially uncorrelated noise sources (the fine grain turbulence).

FIGURE 1.

FAR FIELD NOISE SPECTRA SHOWING AN APPARENT DISCREPANCY of 7dB BETWEEN LOW ($Re < 3\times10^5$) AND HIGH ($Re > 3\times10^5$) REYNOLDS NUMBER.



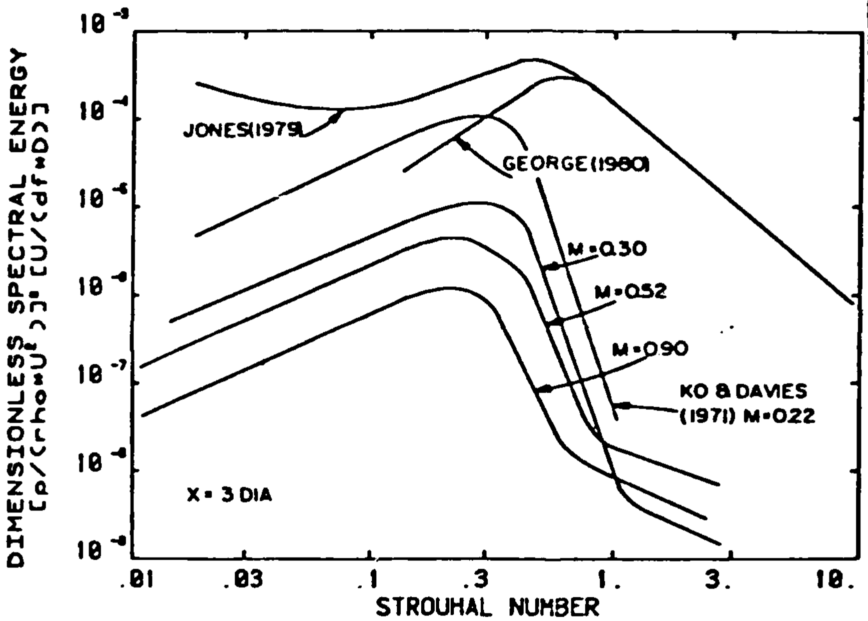
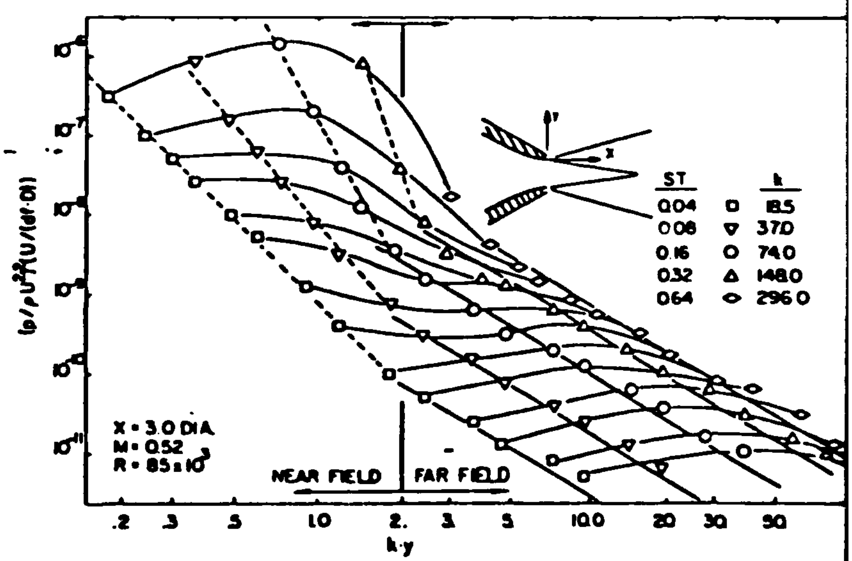




FIGURE 2.

MACH NUMBER EFFECT ON NEAR FIELD PRESSURE FLUCTUATIONS.

FIGURE 3.

EVOLUTION of PRESSURE FLUCTUATIONS FROM ~~NA~~ NEAR TO FAR FIELDS.



## Analysis of Near Field Pressure Spectrum

Theoretical analysis of the observed features of the near field pressure spectra has been initiated. The near field pressure spectrum can be described in terms of four regimes:

1. Low wave number region $S(k) \sim k$
2. Energy containing scales $\sim S(k) \sim k^{0}$ (flat)
3. Inertial subrange $S(k) \sim k^{-6}$ to $k^{-8}$
4. Far field - observation point is more than two wavelengths from the source - $S(k) \sim k^{-2}$

It is also observed that only the energy containing scales decay with the expected 18dB per doubling of distance in the near field.

The latter observation is explained by the geometry of the measurement scheme. The expected spatial decay is in terms of varying the distance to the sound source. At low wave numbers (see Fig. 3), doubling $y$ is not equivalent to doubling this distance.

Of the former observations, the acoustic model is thus far able to predict the very steep slope of the spectrum in the mid frequencies. Work is continuing to identify pertinent features of the near field signal that can be used as a diagnostic to determine in a quantitative fashion the role of coherent structure in the acoustic radiation process.

## Acoustic Excitation as a Method for Studying Coherent Structures

A now classic technique is to introduce small amplitude acoustic disturbances of appropriate frequency. This tends to bring the large scale structure into greater coherence. In effect, the wave-like motion is phase-locked to the excitation signal.

Becker and Massaro (1969) used smoke visualization to determine that a naturally developing jet at a Reynolds number less than 20,000 showed little evidence of coherent structure. Acoustic excitation with a loudspeaker caused the presence of readily observable axisymmetric vortices which were observed to "pair" into larger structures. Beavers and Wilson (1970) observed similar vortical motions at lower Reynolds number (3000) without excitation, but were unable to see distinct vortex structures at higher Reynolds number.

In a landmark paper, Crow and Champagne (1971) found evidence that the same type of orderly structure exists in a high Reynolds number jet as was previously observed in low Reynolds number jets. Coherent structures were enhanced by acoustic excitation at forcing frequencies comparable to those at which the bulk of the turbulent energy is found ($\frac{fd}{U_j} \simeq 0.3$). Acoustic excitation results in a wave-like structure dominating the turbulent field over the first five to six diameters of the flow at the expense of the fine grained turbulence.

Kibens (1980) suggests that the initial shear layer instability (sensitive to much higher frequencies) can be coupled to the column mode instability studied by Crow and Champagne through the mechanism of vortex pairing. He demonstrated this by exciting the initial shear layer of a jet at the most highly amplified frequency, $f_e$ (in this particular case $f_e d/U_j = 3.54$). This excitation enhanced and stabilized large axisymmetric eddies which were observed to pair at discrete positions in the jet. The vortex pairing sequence produced frequencies $f_e/2$, $f_e/4$, and $f_e/8$ in the flow field. Maximum coupling occurs when

$$\frac{f_e}{8} = f_c \text{ or } \frac{f_e}{2^n} = f_c \qquad n = \text{an integer}$$

where $f_c$ is the column mode frequency. This is illustrated in Figure 4 which is based on the work at the University of Minnesota. The dotted line is a plot of $8f_c$ vs. velocity as measured in a 7.1 mm jet. Superimposed on this plot are the calculated most unstable frequency in the laminar shear layer for both an axisymmetric disturbance, $f_o$, as well as a spiral disturbance, $f_1$, (amplification rates at the given unstable frequency are about equal).* Excitation in this case is at a constant frequency of 40 KHz. The velocity is varied such that either the helical mode or the axisymmetric mode is cominant. Typical far field noise spectra are shown in Fig. 5. At $M = 0.21$, the axisymmetric mode is dominant and the noise spectrum contains tones at $f_e = f_o$ and its <u>subharmonics</u> as well as non-linear interaction tones, $f_o/8 + (f_1 - f_o)$, $f_o/4 + (f_1 - f_o)$, etc. At slightly lower Mach number, $M = 0.20$, the helical mode is dominant and jet noise is <u>suppressed</u> by approximately 8dB. Comparable results are observed by Zaman and Hussain (1981) in the polential core. <u>This result opens up new vistas in terms of jet noise research.</u>

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*These frequencies scale with momentum thickness which in a laminar shear layer scale with $U^{-1/2}$ power. Hence $f_u \sim U^{3/2}$.

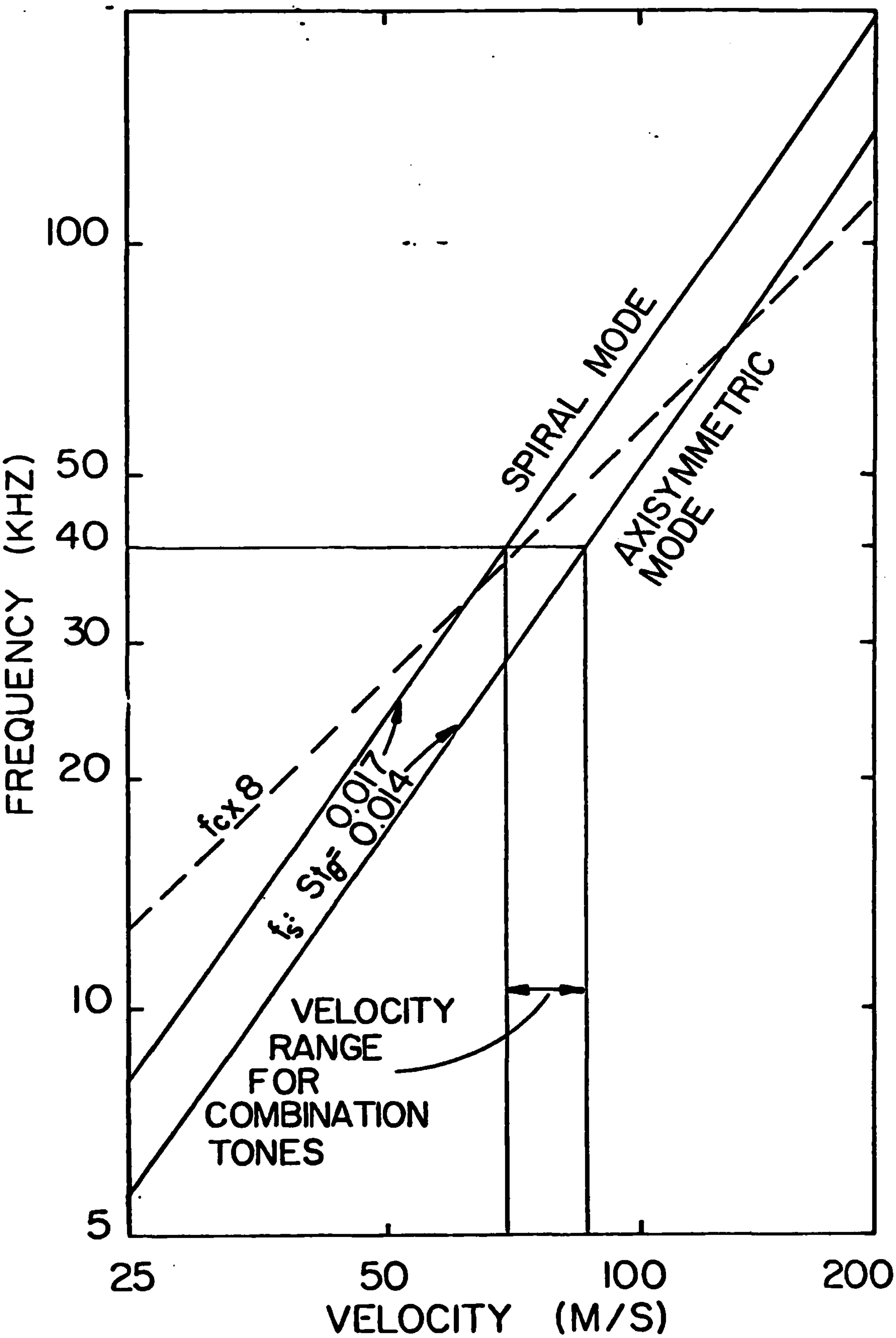


Fig. 4. Frequency-velocity relationship for column mode instability.

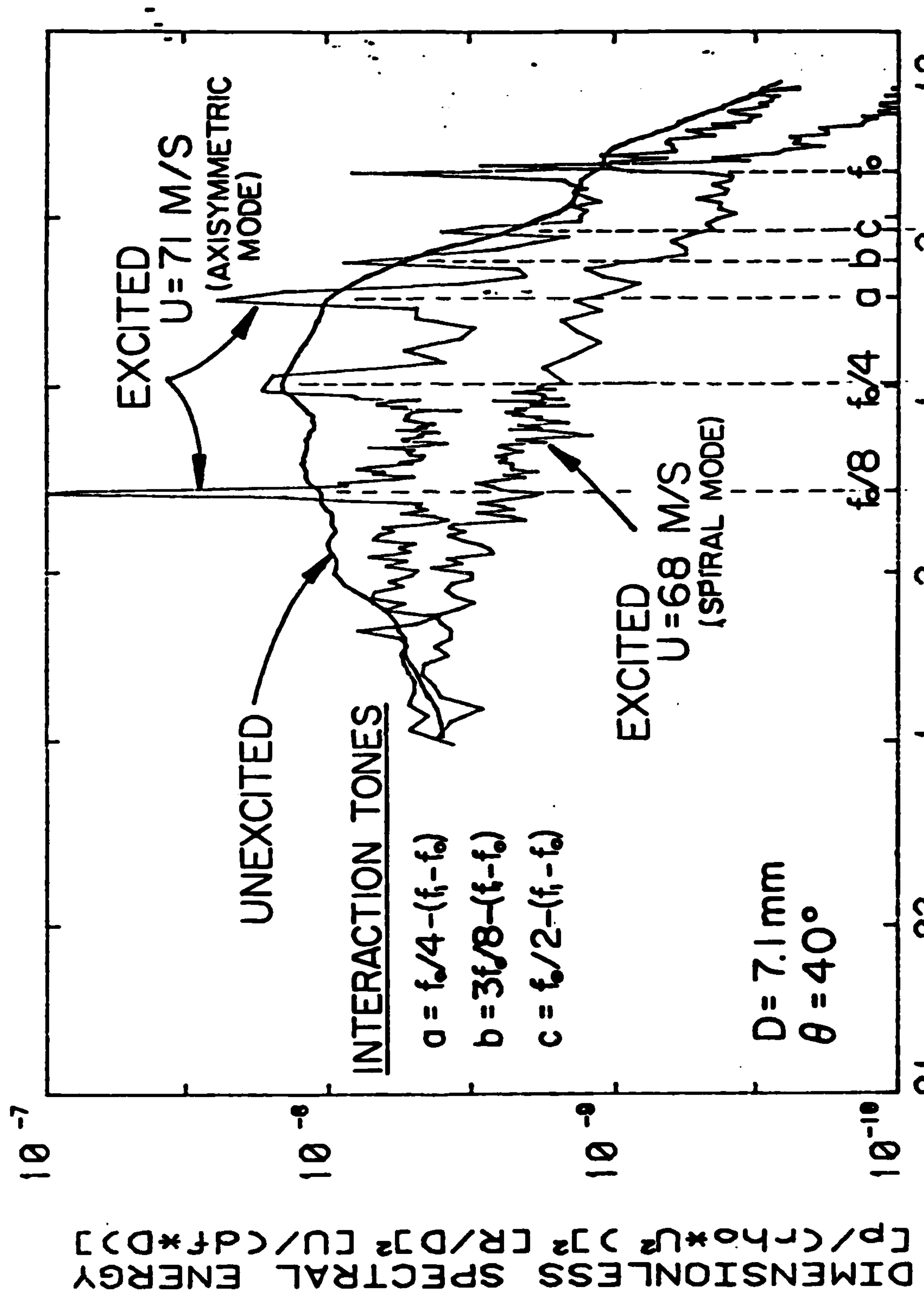


**Fig. 5. Comparison of far field spectra from a 7.1 mm jet, 1) natural development, 2) excitation of axisymmetric mode, 3) excitation of spiral mode.**

Kibens work and the work at the University of Minnesota dealt with jets at relatively low Reynolds number ($Ud/\nu \leq 5 \times 10^4$). Our work, as well as earlier work of Yamamoto (1978), indicate that jet noise at low Reynolds number ($<10^5$) is relatively less intense than high Reynolds number jets and that there are differences in the spectral characteristics as well. It may very well be that at higher Reynolds number the coherent structure in a jet plays a more passive role. Both Bechert and Pfizenmaier (1975) and Moore (1977) found a significant <u>increase</u> in the broad band level of jets at high Reynolds number ($>10^5$), when forced at frequencies comparable to the column mode instability. In his review of aeroacoustics, Crighton (1981) shows that excitation at Reynolds numbers in excess of $10^5$ results in <u>increased</u> broad band noise and conversely excitation at Reynolds numbers below $10^5$ results in <u>decreased</u> broad band levels (albeit there can be dominant pure tones in the signal). Another important point is that noise spectra are independent of flow speed, i.e. Helmholtz number, $fd/a_o$, is a better frequency scaling parameter. This is also true for <u>unforced</u> jets at low Reynolds number (Long, et al 1981).

## SUMMARY

An overview of the literature indicates that coherent structures in turbulent jets have been observed in naturally developing jets especially at low Reynolds number. Detailed study requires either acoustic excitation to bring the coherent portion of the turbulent motion into greater prominence or the use of conditional sampling techniques. Flow visualization is an important experimental technique. As a first step in mathematical modelling, we have examined in detail the theoretical models that have already been constructed to determine the relevance of these structures to the jet noise problem. These models fall into four main categories: 1. discrete vortices, 2. instability waves, 3. vortex pairing, 4. large scale - small scale interaction. The instability wave model has received the most attention. The mathematical development from "first principles" is straight forward but the details are rather complicated. The latter two models are more complex theoretically. The vortex pairing model is really a subset of the interaction model since vortex pairing can be considered as the interaction of two large structures. When the pairing process is isolated, there is evidence - both theoretical and

experimental - that pairing produces a sufficiently violent turbulent field to account for the observed noise. When this model is extended to vortex interactions from all different sizes, one obtains the broad band noise spectrum observed. It is also possible that the large structures merely modulate the noise produced by more conventional turbulent sources but play no active role in the production itself. This idea is feasible but has not received sufficient mathematical treatment as yet. In fact, when one looks at the evidence to date; that at low Reynolds number, the noise field is somewhat less energetic and that the spectrum at all angles scales best with Helmholtz number, that forced jets produce a radiation pattern that scales with Helmholtz number, and that broad band noise is suppressed by acoustic excitation at low Reynolds number and enhanced at high Reynolds number; a pattern begins to emerge. It may be that at sufficiently low Reynolds number direct acoustic radiation from vortex pairing events can be a dominant noise source which is enhanced by bringing the coherent structure into greater dominance by acoustic excitation. At sufficiently high Reynolds number, noise due to the interaction of the wave-like structure with incoherent fine-scale turbulence may be dominant. Acoustic excitation enhances the wave-like structure, but at the same time the interaction noise is enhanced resulting in a higher broad band level.

A summary of the significant observations on the nature of coherent structure and the supporting theoretical developments is presented in Table I. Space limitations do not permit discussing this in detail. The important point is that there is not one unified theory that can explain all of the experimentally observed characteristics of coherent structures. This implies that future mathematical models will require an even greater degree of sophistication.

Our future plans are to continue the work begun with acoustically excited jets. Flow visualization will be used to determine the differences in flow development during different stages of excitation. These results will be correlated with measurements of sound source distribution. It is intended that these results will aid in constructing a useful mathematical model of the acoustic radiation process.

TABLE I: SUMMARY OF EXPERIMENTAL OBSERVED CHARACTERISTICS AND THEIR THEORETICAL FOUNDATION

| OBSERVATION | METHOD | SUPPORTED BY | MODEL SUPPORTED |
|---|---|---|---|
| Broad band increase in radiated noise with excitation | Plenum excitation | Moore (1977)<br>Bechert and Pfizenmaier (1975)<br>Schmidt (1978) | Wave model of Ffowcs Williams and Kempton (1977) |
| Broadband decrease in radiated noise | Shear layer excitation | Kibens (1980) | Pairing model |
| Significant Reynolds stress production during vortex pairing | Conditional sampling | Browand and Weidman (1976) | Pairing model |
| Normalized acoustic power output is less below $Re=10^5$ | Low Reynolds number and excitation | Long et al (1981)<br>Yamamoto (1978) | ? |
| Helmholtz scaling works better in the presence of large structures than Strouhal scaling | Low Re and excitation | Long et al (1981)<br>Moore (1977) | ? |
| Noise amplitude independent of excitation amplitude | Excitation | Moore (1977) | Modifying effect of large structure |
| A spike in U signal is correlated with a spike in far field pressure | Conditional sampling | Juve et al (1980) | Vortex interaction (pairing) |
| Similarity between turbulence spectra and far field spectra | | Fuchs (1979)<br>Fuchs and Michel (1977) | Extended source wave model |
| Possibility of feedback of noise on initial shear layer | | Laufer and Monkewitz (1980)<br>Kibens (1979) | ? |

## II-C SUNY/Buffalo

This year has seen substantial progress toward the goal of applying the orthogonal decomposition to measurements in the turbulent jet mixing layer. Also, the process of developing and maintaining the measuring system has contributed significantly to the state-of-the-art of flow measuring techniques and to the understanding of turbulence.

This program received a major infusion of new equipment in 1979-80 (in part paid for by AFOSR). While this equipment was essential to the conduct of the experiment, it proved to be impossible to rapidly configure it into an operational laboratory, in part because of bugs in it and in part because of our lack of experience with it.

The addition of Dr. Tan-atichat in September 1981, the increased technical competence of the principal investigator (thanks to a recent sabbatical leave), the continued emergence of S. Capp and R. Suhoke, and the addition of several key graduate students have made it possible to complete the assimilation of this new hardward into the laboratory. At this point all subsystems for the jet experiment are operational and can function together under the control of a central processor (PDP 11/34) as required.

Because of the move to a new building in January, a new jet facility has been constructed and experimental work has been initiated in it. A theoretical effort has also been initiated to develop the analytical computational techniques required to actually deduce the large eddies from the experimental data. We are optimistic that the first concrete results from the coherent structure program will be achieved within the next few months.

Significant breakthroughs in the hardware design of the laser Doppler system have been achieved during the last year. Specifically, the burst time and fringe count registers in the LDA counters have been increased from 8 to 10 bits, thereby removing a major source of error in measurement. (These changes have been incorporated by the manufacturer also.) Also several new computational algorithms have been developed which made possible on-line diagnoses of the LDA signal quality, thereby significantly improving the system reliability.

A major problem in existing jet data has been resolved. For many years it has been believed that coherent structures were responsible for the inability of turbulence models to predict the two-dimensional and axisymmetric jet developments. It has been shown during the course of this work that the problem was not due to coherent structures but to incorrect data. These data have been shown not to conserve momentum, both because of measurement errors and because of backflow in the experimental facilities. Correct data obtained with the techniques developed in this experiment have been shown to conserve momentum. Moveover these data are in near perfect agreement with the predictions of the Lumley-Taulbee Reynolds stress model of the turbulence which also accurately predicts the two-dimensional jet.

## III. LIST OF MANUSCRIPTS

### Illinois Institute of Technology

1. Drubka, R. E.,"Instabilities in Near Field of Turbulent Jets and Their Dependence on Initial Conditions and Reynolds Numbers", Ph.D. Thesis, Illinois Institute of Technology, 1981; also appears with H. Nagib as I.I.T. Fluid and Heat Transfer Report R81-2; Technical Report, AFOSR-TR-81.

2. Drubka, R. E. and Nagib H. M., "Turbulent Jets with Controlled Initial Conditions", To appear in I.U.T.A.M. proceedings of Symposium on Structure on Complex Turbulent Shear Flow, Marseille, Sept. 1982.

3. Drubka, R. E. and Nagib, H. M., "Instabilities in Free Turbulent Jets and their Dependence on Initial Conditions", To be submitted to Journal of Fluid Mechanics.

4. Drubka, R. E. and Nagib, H. M., "The Role of Upstream Influence in Free Turbulent Jets", To be submitted to Journal of Fluid Mechanics.

### University of Minnesota

1. Arndt, R. E. A. "What Do We Measure and Why," in Fluid Mechanics Measurements, Hemisphere. To be published.

2. Arndt, R. E. A. et al., "Fluid Mechanics Research in 1980", Journal of the Engineering Mechanics Division, ASCE, Vol. 107, No. EM3, June 1981, pp. 445-454.

3. Arndt, R. E. A. Baker, C. B., and Hoyt, J. W., "A Brief Survey of Polymer Effects on Cavitation Noise", Cavitation and Polyphase Flow Forum, ASME/ASCE Mechanics Conference, Boulder, Colo., June 22-24, 1981.

4. Arndt, R. E. A. "Cavitation Damage and the Tarbela Tunnel Collapse of 1974," (by M. J. Kenn and A. D. Garrod), Discussion, Proc. Inst. Civ. Engrs., Part 1, Nov. 1981, pp. 795-797.

5. Arndt, R. E. A. Long, D., Van Lent, T., "Jet Noise at Low Reynolds Numbers", AIAA Paper 81-1962, AIAA 7th Aeroacoustics Conf., Palo Alto, Calif., Oct. 1981. (Also submitted to AIAA Journal for publication.)

6. Arndt, R. E. A. "Fundamentals of Hydraulic Turbine Design," Renewable Energy Review Journal, Vol. 3, No. 2, Dec. 1981.

7. Arndt, R. E. A. and Long, D., "Noise Radiation from Coherent Structures in Turbulent Flow", Shock and Vibration Digest (to appear).

### SUNY/Buffalo

1. Capp. S. P. & W. K. George, "Measurements in an Axisymmetric Jet Using a Two-Color LDA and Burst Processing" To be presented at the International Symposium on Applications of Laser-Doppler Anemometry to Fluid Mechanics, Lisbon, Portugal, July 5-7, 1982.

## IV. Research Personnel

<u>Illinois Institute of Technology</u>

Hassan M. Nagib, Professor, Principal Investigator

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Ph.D. Degree; Dec. 1981, Thesis title: Instabilities in Near Field of Turbulent Jets and Their Dependence on Initial Conditions and Reynolds Number.

Thomas C. Corke, Assistant Professor

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Mark Jennings, Research Assistant

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R. B. Suhoke, Jr., Technician

DeXiu Peng, Graduate Assistant

Stuart Lieb, Graduate Assistant

Mark Glauser, Undergraduate Assistant

Scott Woodward, Undergraduate Assistant

## V. Presentations

### Illinois Institute of Technology

1. Nagib, H. M. and Drubka, R. E., "Free-Jet Instability and its Dependence on Initial Conditions and Reynolds Number", 34th Physics of Fluids Annual Meeting of the American Physical Society. Abstract appears in APS Bulletin, Nov. 1981.

2. Drubka, R. E., "Instabilities and Subharmonic Evolution in a Free-Jet", 34th Physics of Fluids Annual Meeting of the American Physical Society. Abstract appears in APS Bulletin, Nov. 1981.

3. Drubka, R. E. presented a talk on "Evolution of Axisymmetric, Helical and Subharmonic Instabilities in a Jet and their Dependence on Reynolds Number and Initial Conditions", at a Workshop on Jet Flows at Stanford University, Nov. 1981.

4. Drubka, R. E., presented a seminar at Illinois Institute of Technology entitled "Instabilities in Near Field of Turbulent Jets and their Dependence on Initial Conditions and Reynolds Number", Dec. 1981.

5. Drubka, R. E. presented a seminar at the University of Texas at Austin entitled "The Development of Turbulent Jets", March 1982.

6. Drubka, R. E. presented a seminar at Stanford University entitled "The Nature of Upstream Influence in an Axisymmetric Jet", May 1982.

7. Drubka, R. E. and Nagib, H. M., "Turbulent Jets with Controlled Initial Conditions", I.U.T.A.M. Symposium on Structure of Complex Turbulent Shear Flow, Marseille, Sept. 1982.

### University of Minnesota

1. Arndt, R. E. A., "A Brief Survey of Polymer Effects on Cavitation Noise", presented at Cavitation and Polyphase Flow Forum, ASME/ASCE Mechanics Conf., Boulder, Colo., June 23-24, 1981 (with C. B. Baker and J. W. Hoyt).

2. Arndt, R. E. A., "Jet Noise at Low Reynolds Numbers", Presentation at AIAA 7th Aeroacoustics Conference, Palo Alto, Calif., Oct. 5-7, 1981.

3. Arndt, R. E. A., "Coherent Structure and Noise", Aerospace Engineering and Mechanics Colloquium, University of Minnesota, Feb. 12, 1982.

4. Long, D., "Jet Noise at Low Reynolds Numbers", Acoustical Society of America, Ottawa, Canada, May 1981.

5. Arndt, R. E. A. and Long, D., "Acoustics of Excited and Non-Excited Jets at Low Reynolds Number", Workshop on Jet Flows, Stanford University, Palo Alto, Calif., Nov. 1981.

SUNY/Buffalo

Capp, S. P. and George, W. K., "Turbulence Measurements in a Fully Developed Axisymmetric Jet Using a Laser Doppler Anemometer", American Physical Society Annual Meeting, Monterey, Ca., Nov. 1981.

Khwaja, M.S.S. and George, W. K., "Cross-Correlation and Spectral Measurements in an Axiymmetric Jet Mixing Layer", American Physical Society Annual Meeting, Monterey. Ca., Nov. 1981.

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